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Applications of HCMM Satellite Data to the Study of Urban Heating Patterns

Remote estimate of the surface energy flux, moisture availability and thermal inertia over urban and rural terrain.

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16. Abstract

We have divided our research summary with regard to HCMM into two major areas, one developmental and the other basic science. In the first we discuss three sub-categories: image processing techniques, especially the method whereby we convert surface temperature images to images of surface energy budget, moisture availability and thermal inertia; model development; and model verification. Basic science includes the use of our method to further our understanding of (1) the urban heat island and anthropogenic modification of the surface heating, (2) evaporation over vegetated surfaces and (3) the effect of surface heat flux on plume spread. We conclude with some recommendations for the future.

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Figure 2. Technical Report Standard Title Page

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Preface

Our original proposal to NASA entitled "Applications of HCMM Satellite Data to the Study of Urban Heating Patterns" was prompted by opportunity to make use of thermal imagery obtained from a rather unique satellite and by a need to understand the relationship between the nature of the surface canopy and the surface heat flux. It was clear from studies done at Penn State and elsewhere that spatial variations in surface heat flux can force significant horizontal and vertical air motions in the atmosphere. The importance of surface heating also extends to the transport of atmospheric pollutants and the dispersion of pollution plumes because turbulent motions are intimately related to the rate of surface heating.

The most important region where profound surface heat flux variations exist and where anthropogenic modifications of the surface canopy are known to influence the local meteorological conditions is the city. Urban heat islands have been recognized for some time as man-made entities. The results of METROMEX in St. Louis (Changnon, 1978) and the findings of Harnack and Landsburg (1975) for Washington, D.C. offer sound evidence that the patterns of heating over a city can produce convergence in the boundary layer in such a way as to alter, and even enhance, the convective precipitation over and downwind of the city. Thus, there arises the need to model the distribution of surface heat flux over different types of terrain.

Our examination of the surface temperature patterns over a city (Los Angeles, for example) revealed to us that the surface heating is uniquely tied to the character of the land use. In trying to model the surface heat flux, however, it became apparent that any desired variation in surface temperature or heat flux could be generated, provided that the surface parameters were set accordingly in the model, a situation that would seem to indicate that the problem of remotely measuring surface heat flux is insoluable. Sensitivity test with a model developed by Carlson and Boland (1978) indicated that there are two principal unknowns that govern the surface heating; the thermal inertia and the moisture availability. They showed that all remaining parameters in the model could be estimated from a general knowledge of the terrain or determined from routinely measured meteorological variables. The implication was that aside from the two dominant parameters, the surface heat flux could be calculated to within a reasonable error using available measurements. Although the dominant surface parameters are basic unknowns, we felt that they could be inferred from satellite data.

The problem we set ourselves in the HCMM project was to determine a method for obtaining the two dominant parameters from satellite imagery. We suggested that this could best be accomplished by matching surface temperature variations, as measured by a satellite, to those simulated in a model, defining the correct values of the dominant surface parameters as those which uniquely prescribe the measured surface temperature variation. We found that a matching technique for obtaining two model unknowns given the surface temperatures was feasible, provided that two temperature measurements within the same daily temperature cycle were available, preferrably near the times of maximum and minimum temperatures. HCMM provided this data source, being the first operational satellite possessing an infrared sensor with a day/night schedule near the times of maximum and minimum temperature.

By the time HCMM was launched in 1978, we had already developed a method for combining a one-dimensional model of the boundary layer with an analysis of thermal imagery for the purpose of determining values of the surface heat flux and the governing surface parameters.

The method was subsequently tested with the HCMM data for various cases. Out of this effort came three student masters theses, three journal articles (Carlson et al. 1981; Carlson, 1981, Carlson and DiCristofaro, 1981) and various new ideas concerning the applications of thermal imagery to the analysis of surface heat and evaporative fluxes. One idea that occurred to us rather early in the research was the realization that if surface heat fluxes could be determined by our method, so also could the evaporative fluxes. At this juncture, our interests began to diverge from the original project directive, which was to determine the heat flux over urban heat islands. Thus, we began to consider the measurement of evaporative fluxes and soil moisture over vegetated surfaces as a worthy application of the method. We found that an innovative European group based in Holland and in Ispra, Italy was working along similar lines in using a boundary layer model to infer surface evaporation in conjunction with satellite temperature measurements. However, we were the first to demonstrate the feasibility of transforming day/night temperature images onto maps of surface moisture, as expressed by the moisture availability parameter.

The most important of our HCMM results was therefore the demonstration that satellite data can be used to determine, or at least estimate, surface heat flux and evaporation, as well as the thermal inertia and moisture availability, over a heterogeneous terrain. A second general result of the project was our own increasing familiarity with the relationship between surface heating and land use and the understanding of how to put such knowledge to use in numerical modeling. DiCristofaro, in his MS thesis (1980), was able to show how different types of land use downwind from a power plant can influence the spread and concentration of plumes from an elevated source.

Some curious conclusions were obtained by Carlson et al. (1980) as the result of the Dodd (1979) MS thesis work. Dodd found that the familiar urban heat island may exist (at least in summer) not so much because urban materials are highly conductive and heat retaining, as always surmised in the literature, but because there is greater heating over urban surfaces during the day due to the absence of vegetation and the dryness of the surface. Thus, variations in moisture and in surface heating are greatly modulated by the distribution of surface materials, especially the vegetation cover. Kocin's (1979) M.S. thesis, which was devoted almost exclusively to the determination of evaporation and heating over a highly vegetated region, suggested that rainfall may be a secondary but important factor in determining the evaporation over totally vegetated surfaces. In general, well-watered vegetated surfaces, especially forests, possess evaporation values that are likely to be very close to the potential evaporation (equivalent to a moisture availability of 1.0).

Current efforts are being directed toward the introduction of derived surface parameters into mesoscale numerical models, using an interactive approach. One of the significant advances we made was in the development of a new procedure for analyzing satellite imagery in conjunction with numerical boundary layer modeling. The method involves linking together both image analyses and a boundary layer model to produce results that can be used in mesoscale numerical models. We have recently adopted a partially interactive mode of image processing, in which satellite imagery is displayed, manipulated, and stored within a minicomputer linked to an image processor and video monitor.

Further conclusions and recommendations are included at the en. of the main body of this report. Subsequent discussion will include a summary of the research performed over the past three years followed by specific conclusions and recommendations. The report will treat the research in two branches: the data manipulation and image processing system and the model development and use. References will be made to existing documents previously sent to NASA but the important aspects of this work will be highlighted here.

1. Introduction

The principle goal of our HCMM work was to develop a method for inferring from satellite data the surface energy budget and the values of the parameters that govern the surface heat flux over urban terrain. Carlson and Boland (1978) developed a boundary layer model and suggested a way in which that model could be used to obtain the two governing parameters, which they called the moisture availability (M) and the thermal inertia (P). The need to obtain the governing surface parameters for use in numerical models emerged due to the principal investigator's association with a numerical modeling group in the meteorology department, which was engaged in trying to produce forecasts of air motion over mesoscale regions with variable terrain. We noted that surface heat flux, an important factor in driving boundary layer circulations, could vary by an order of magnitude across heterogenous terrain such as a city. Our basic idea in using satellite data was to match the measured surface temperatures from the satellite against simulated surface temperatures from a model, defining the correct values of the governing parameters as those which result in the best fit between the measurements and the simulated temperatures.

Fortunately, Carlson and Boland found that the matching technique was able to define the governing surface parameters uniquely (most of the time), provided that the surface temperatures could be measured near the time of maximum and minimum temperature, preferrably on the same day. HCMM was an opportunity to test these ideas because that satellite was the first operational one that met the forementioned criteria. Moreover, HCMM resolution was very suitable for detailed analysis of surface temperature patterns. Our initial efforts were directed toward developing a computerized system for manipulating a temperature image, rectifying both day and night images to fixed coordinates, transforming those day/night temperature pairs to maps of the governing parameters using the one-dimensional boundary layer model, and finally drawing the transformed images on map backgrounds. A collateral investigation involved a constant revision and improvement of the boundary layer model.

2. Methods

2.1 The boundary layer model

Fig. 1 summarizes the method we used to obtain the maps of M, P, surface heat flux (H_o) and surface evaporation flux (E_o). The operations referred to above the dotted line in the figure refer only to output by the one-dimensional boundary layer. By prescribing all of the model parameters (moisture availability, thermal inertia, surface roughness, wind speed, surface albedo, etc.) one can generate the rate of heat, moisture and ground flux, as well as the surface temperature as a function of time at one location. Carlson and Boland show that provided M and P are known, routine measurements of mean wind speed and large scale atmospheric stability, along with reasonable estimates of the surface roughness length, albedo, etc. are sufficient to allow the temperature and heat

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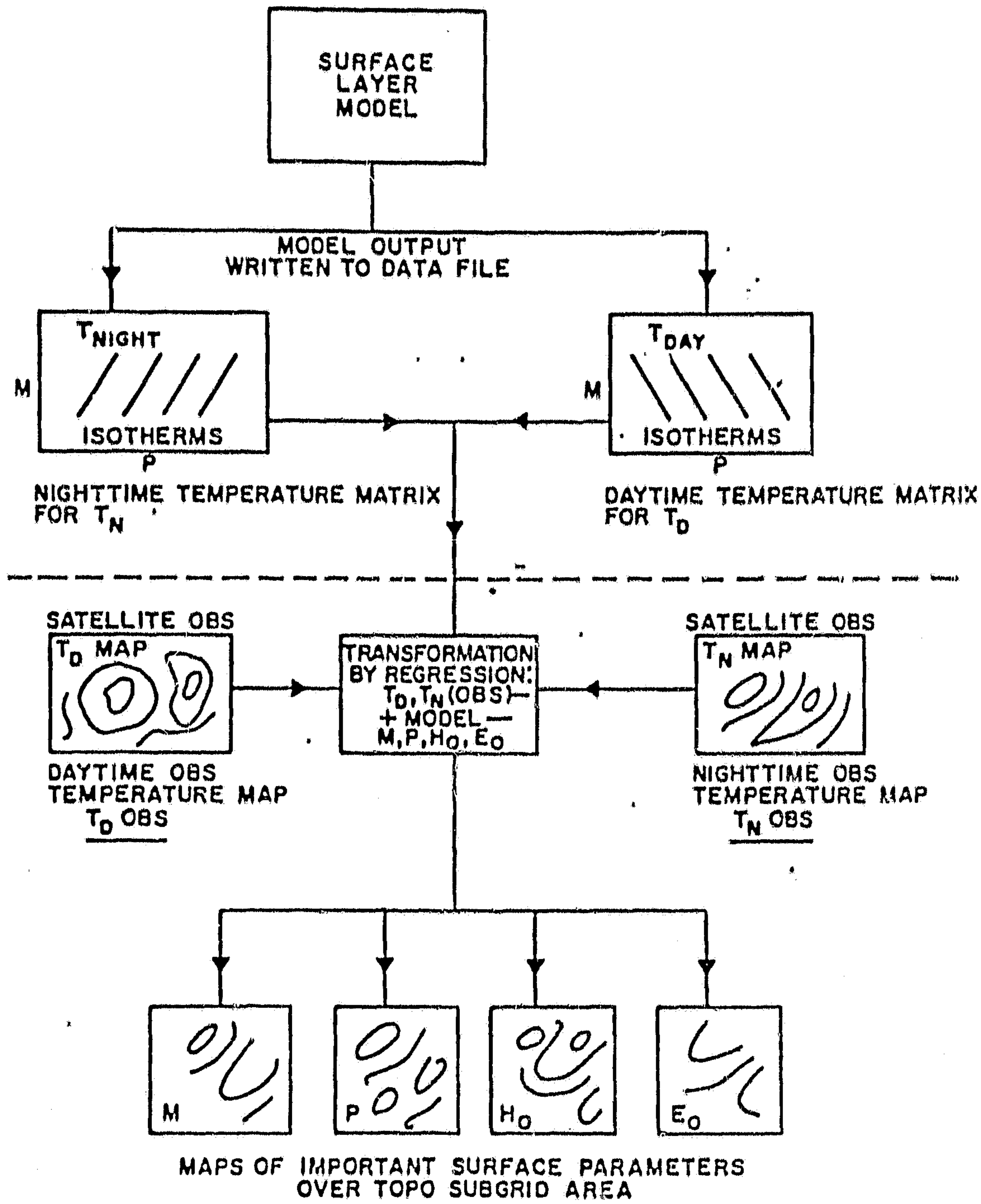

Fig. 1 Flow diagram for inferring surface parameters. (From Dodd, 1979)

flux to be calculated to within an error of about ± 2°C and ± 20%, respectively (see Section 3.6). By far the greatest variations in surface temperature and heat flux are produced by variations in M and P. Thus, if M and P can be determined, the variation of surface temperature, surface heat flux and evaporation can be calculated in any physically realistic boundary layer model using those derived parameters. The problem becomes soluable by realizing that if two temperatures at two different times along the daily temperature cycle are provided, for example by direct measurement with a satellite, the two dominant model unknowns, M and P, can be inferred. To determine M and P we formulated an inversion scheme whereby the two parameters were obtained by matching model results with model simulations. The sequence by which model results are matched to direct measurements to obtain the analyses of M, P and the surface fluxes is outlined below the dotted line in Figure 1. A more detailed description of the model is presented in Appendix I.

Although M and P can be considered in an abstract sense as model constants which yield the correct (observed) temperature variation at the surface in a numerical model, these parameters also correspond to real physical effects. Thermal inertia describes the ability of the substrate to conduct and retain heat and moisture availability is the ratio of evaporation to potential evaporation. Over bare ground, M is a measure of the surface water content, while over vegetation it is related to the bulk stomatal resistance of the canopy (see Appendix I). Over built-up areas, the moisture availability is related to the fraction of vegetation cover.

2.2 Image Processing

As we have mentioned, our main interest in the beginning was to investigate the urban heat island and the complex patterns of heating associated with cities. We designated St. Louis, MO, Los Angeles, CA, Houston, TX and Washington, DC as the four principal target areas for which we would receive HCMM images and tapes. We were able to complete a total of one HCMM case study for Los Angeles, two for St. Louis (plus one using TIROS-N) and one for Washington, DC, plus one using TIROS-N data for Houston. An additional case study was made for the Clarksville, TN area. A single night image for the State College area was analyzed for the purpose of examining the temperatures over a rough, vegetated terrain at night. Altogether four urban day/night pairs were analyzed. (These analyses are contained, in part, in Dodd's (1979) MS thesis, in DiCristofaro's (1980) MS thesis and in articles by Carlson et al. (1981) and Carlson and DiCristofaro (1981).) Further analyses, not presented in these documents, are contained in Appendices II and III. A complete list of the HCMM images analyzed is contained in Appendix IV.

Our system for extracting the raw HCMM brightness intensities and converting those data to temperature images is outlined in Fig. 2. (This computerized system currently is being replaced by an interactive one involving a minicomputer.

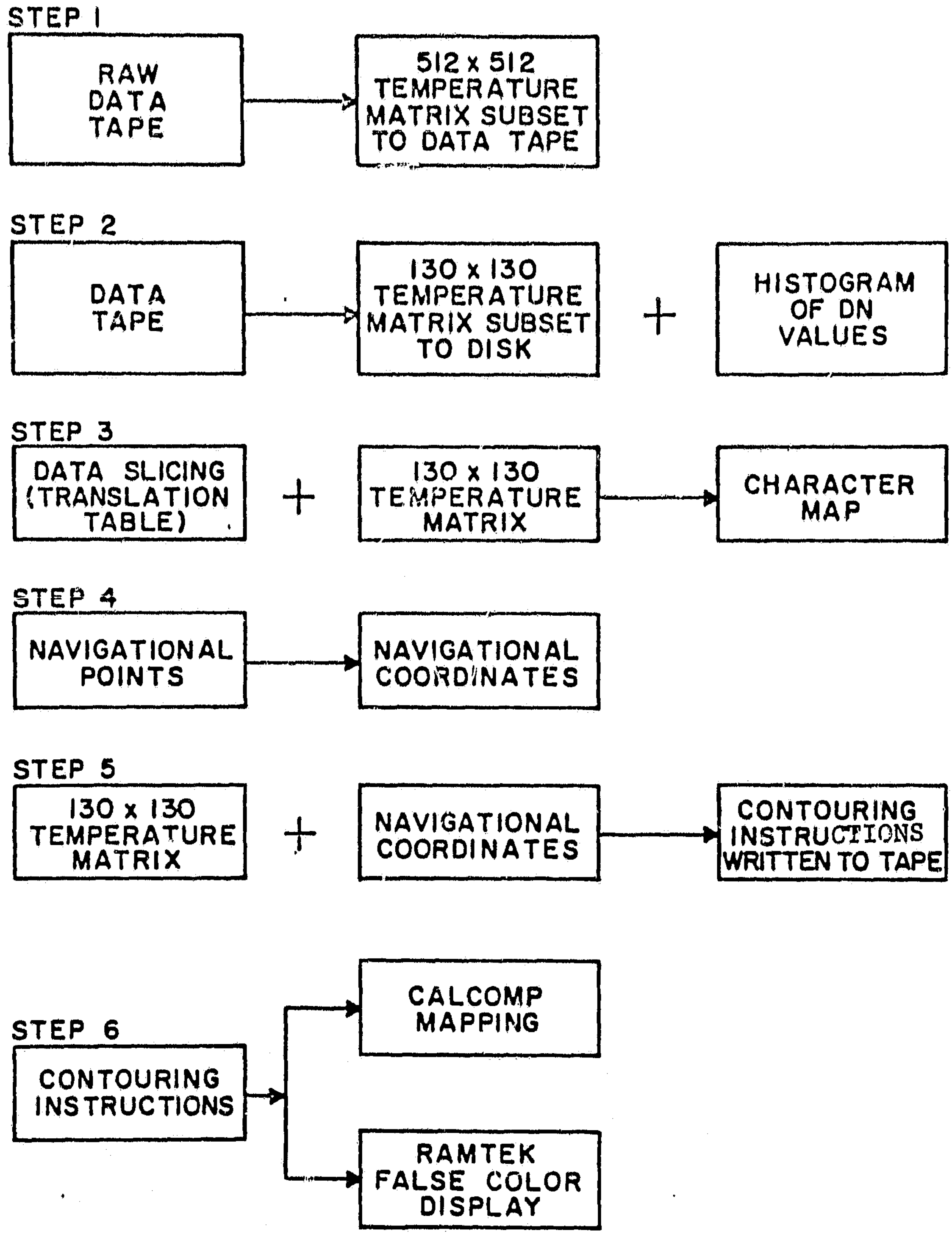

Figure 2. Schematic diagram of the satellite data processing procedure. (From Dodd, 1979)

At present, however, steps 5 and 6 are being performed in batch processing mode on the IBM 370.) The conversion of brightness units to temperatures is made using the formula suggested by NASA (Bohse et al., 1979), with an additional correction for a calibration error and for water vapor absorption (see Section 3.6). Following step 6 in which the unrectified temperature maps are either contoured or displayed on a video monitor, an extracted 130 x 130 working area is mapped to a fixed grid (called a "topo" grid) for both the day and night images. Subsequently, the boundary layer model is executed. A set of regression equations, determined from the model, is used to transform every pair of day/night temperature values in the topo array to values of M, P, and the surface fluxes. Finally, these derived fields are contoured on a conventional map background. As an example of a full 130 x 130 analysis, we present that for surface heat flux over St. Louis (Fig. 3). High values can be found over the downtown area and over the industrial region of Granite City (labelled G). Lower flux values appear over suburban areas, while the lowest heat fluxes can be found over forested areas (labelled F). The patterns of heat flux viewed in this figure closely resemble that obtained in the other HCMM St. Louis case presented in Dodd's (1979) thesis and for the TIROS-N case (not presented). The significance of these results will be discussed in section 3.1.

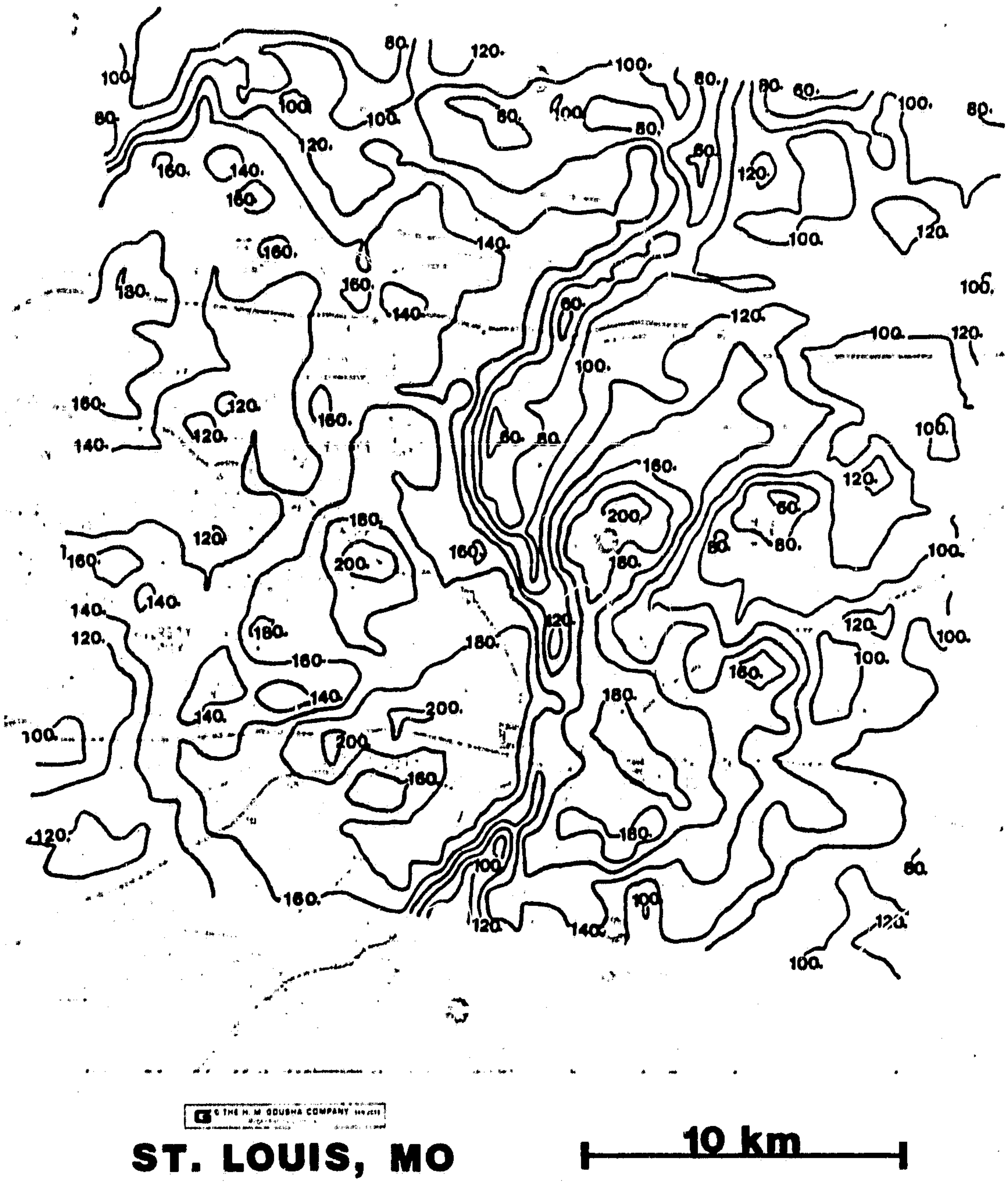

Fig. 3. Surface heat fluxes over St. Louis, 23 August 1978 at about 1330 LST. Values are in Wm^{-2}. (From DiCristofaro (1980)).

3. Results

Our HCMM research can be divided into two main areas: case study analyses and system or model development. The former can be further subdivided into (1) urban heat island studies, (2) investigation into the determination of evaporation over vegetation cover, (3) the effects of land use on power plant plume spread.

These three topics approximately correspond to the theses of Dodd (1979), Kocin (1979), and DiCristofaro (1980), although there is some overlap. Model development has been an ongoing project but major advances made since the start of the HCMM project were reported by Dodd (1979). System development was made in two major steps, one of which was carried out during the period just prior to the receipt of our first HCMM data tapes. A second period of system development occurred during the past year in which our entire image processing scheme referred to in section 2.2 was implemented on the department's minicomputer in an interactive mode of operation. Present efforts involving another student, Arthur Polansky, are directed toward streamlining the boundary layer model for the purpose of installing the model on the minicomputer.

A third area of research has been concerned with model verification. Although verification studies did not directly utilize HCMM data, we feel that the ultimate value of satellite imagery (such as HCMM) for determining surface heat flux or evaporation must depend, in part, upon the reliability of the model. Don DiCristofaro and James Cooper, another student have been attempting to use independent measurements of surface heat flux to test the model. These results will be referred to in section 3.4.

3.1 Urban Research

Several urban case studies using HCMM involved a study of the urban heat island. Altogether we analyzed four cases, two for St. Louis, one for Los Angeles and one for Washington, D.C. It is evident that the urban heat island is a very pronounced and highly detailed phenomenon. Moreover, examination of the imagery alone attests to the persistence of urban temperature patterns and widespread nature of the phenomenon. As noted by Matson et al. (1978), even relatively small urban centers exhibit a heat island. We have found that cities of only a few thousand inhabitants may be reflected in both the day and night temperature patterns.

Perhaps the single most important aspect of our research is that we were first to map the temperature distribution, surface energy balance, moisture availability and therma inertia over any region using satellite temperature data. Our results show that variations in the two parameters M and P, referred to in section 2.1, can, indeed, account for the observed temperature anomalies over urban areas. Regions of relatively warm daytime temperatures correspond to minima in moisture availability; whereas, regions of relatively high nighttime temperatures may correspond to maxima in thermal inertia. We had anticipated that urban areas would exhibit maxima in P, reflecting a greater conductivity and heat capacity of the substrate. Although the centers of the cities were found to be somewhat warmer at night than their surroundings, the distribution of thermal inertia was surprisingly ill-defined over urban areas, with only a slight elevation of P values over some urban centers. This unexpected result can be explained by the fact that the model interpreted the warmer nighttime temperatures over the city to be due to the enhanced daytime warming in those areas. Such warming, which is the result of the dry surfaces, produces greater heat storage in the ground during the day. The conclusion that daytime heating rather than substrate conductivity is responsible for the nocturnal heat island (at least in summer) differs from previous suppositions published in the literature.

One additional result we found to be puzzling was the relatively low values of the Bowen ratio (the ratio of heat flux to evaporative flux), which was only about 1.0 (corresponding to M values less than 0.3) over the interior of the city. Over the suburbs the Bowen ratio was less than 0.5 (corresponding to M values of 0.4 - 0.7); while over thickly vegetated surfaces, such as forests, the Bowen ratio was about 0.1 - 0.2 (corresponding to M values of 0.7 - 1.0). Although one cannot hope to verify such numbers directly, we do find that the values of M appear to remain within reasonable bounds, being close to 1.0 over dense vegetation or water surfaces and less than 0.2

(but greater than zero) over dry surfaces such as industrial parks, etc. Moreover, the Bowen ratios appear to be comparable in the suburban areas to those calculated by Kalanda et al. (1980) for Vancouver, B.C. Thus, we feel that our heat flux patterns are at least qualitatively correct.

The results of METROMEX (Braham and Dungey, 1978; Braham and Wilson, 1978; Huff and Vogel, 1978; Changnon, 1978; Kropfli and Kohn, 1978; Wong and Dirks, 1978; Shreffler, 1979; Vukovich and King, 1980) suggest that important rainfall anomalies in the vicinity of St. Louis can be traced to perturbations in the boundary layer produced by intense surface heating over a region between downtown St. Louis and Granite City. This is indeed the location where we found the strongest surface heating. Consequently, we must conclude that the urban heat island, at least in summer, is directly attributable to the presence of surfaces that do not retain moisture; therefore, human alteration of the surface, and especially the removal of vegetation, constitute, a root cause of the urban weather anomaly. We would like to suggest further that the discomfort felt by humans in big cities on hot summer days is not so much due to the somewhat elevated air temperature in the city, but the greatly elevated surface temperature which would be felt as radiated energy.

3.2 Evaporation and Surface Heating over Vegetated Surfaces

We find that over densely vegetated surfaces, the values of M are consistently between 0.7 and 1.0 and the Bowen ratios are less than 0.2. Kocin's (1979) thesis reveals a wealth of detail in the patterns of surface temperature, and consequently in the patterns of M, P and the surface fluxes over a vegetated watershed region. Figures 4 and 5 illustrate, respectively, the distribution of M and rainfall over the Goodwater Creek watershed area in Missouri during a period in June 1978. Although we could find no apparent relationship between M and the type of surface canopy, except for the town of Centralia which exhibits low values of M, comparison of Figures 4 and 5 suggests some association between the pattern of rainfall amounts for the previous week and the distribution of M, where lower values of the former correspond to lower values of the latter. Thus, while M may be considered an indicator of vegetation cover over a mixed vegetated and non-vegetated surface, this parameter may also reflect the ability of a particular vegetation canopy to transpirate. Indeed, it can be shown that M is related in the model to the bulk stomatal resistance over a vegetated canopy (or to an effective fraction of moisture saturation for bare surfaces). Kocin's thesis illustrates the potential use of satellite measurements in determining patterns of evapotranspiration.

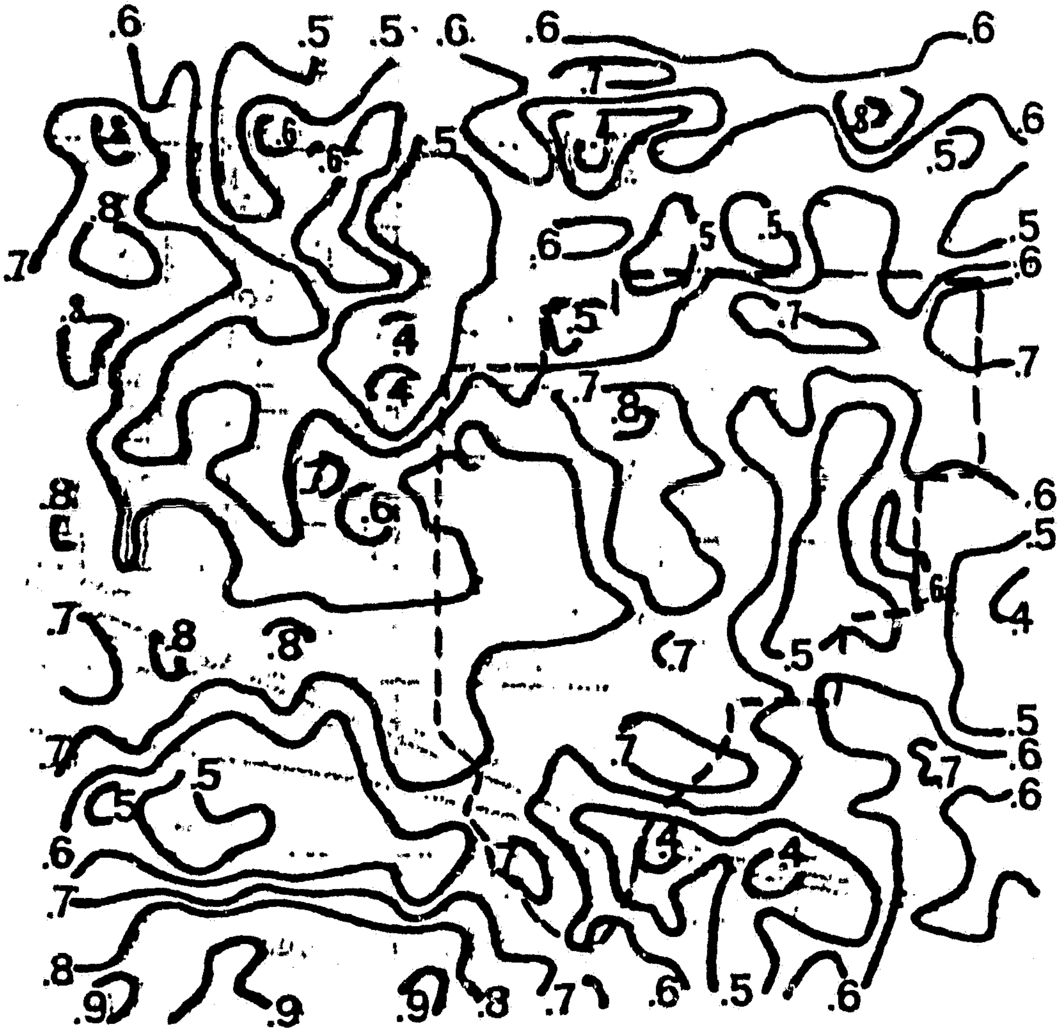

Fig. 4. Moisture availability over the Goodwater Creek watershed (dashed border), 9-10 June, 1978. (From Kocin, 1979).

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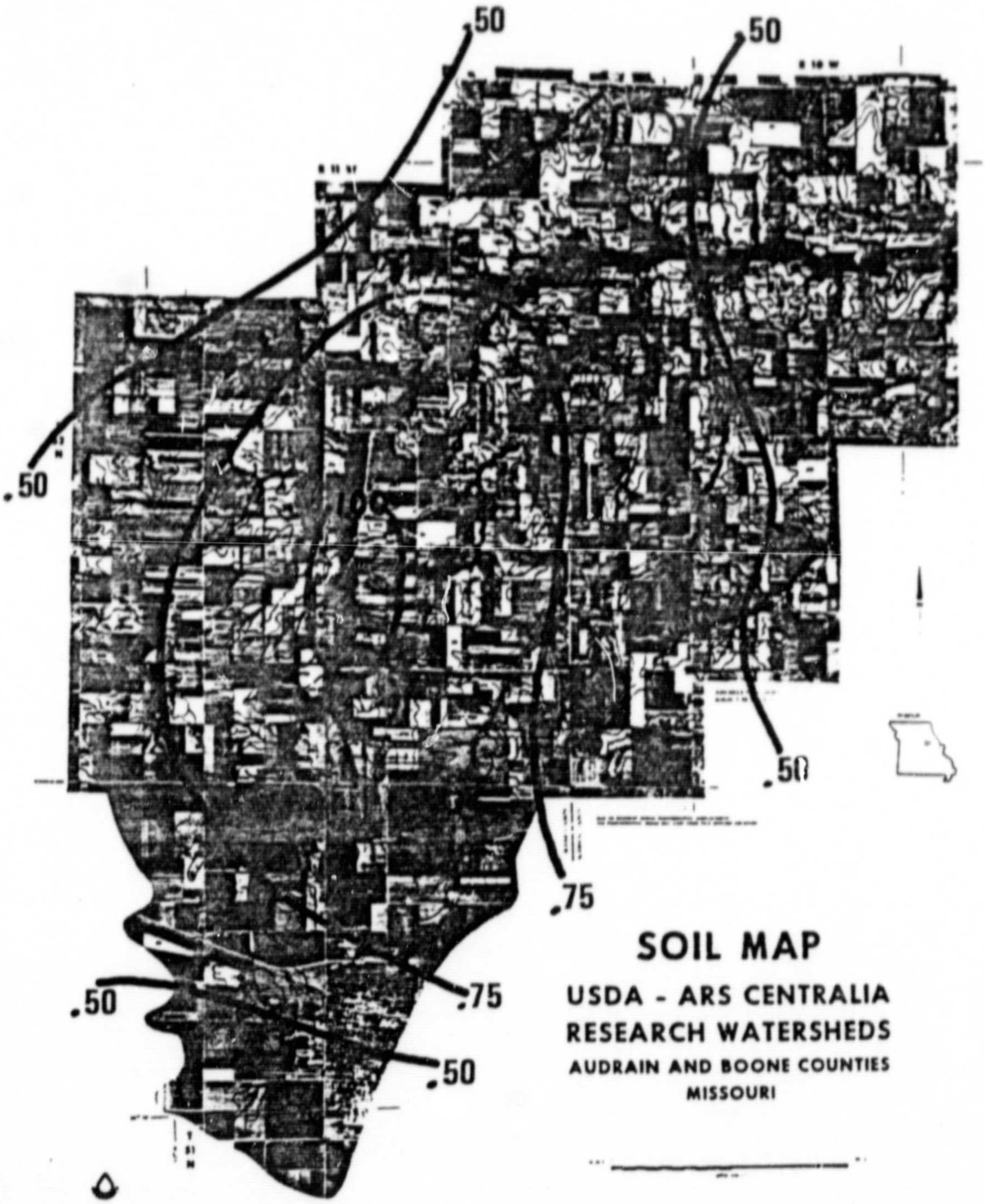

Fig. 5. Rainfall amounts (in inches) over the Goodwater watershed, 1-7 June, 1978. (From Kocin, 1979)

3.3 Differential Surface Heating and Power Plant Plume Dispersion

Surface heat flux and turbulence are intimately related in the planetary boundary layer. For a given mixing depth the vertical friction velocity (essentially the mean vertical velocity of the turbulent eddies in the surface layer) is proportional to the cube root of the surface heat flux. Turbulence can affect the motion and spread of a plume emanating from a local pollution source, such as a power plant. Willis and Deardorff (1978) used a laboratory model and Lamb (1978) used a numerical model of the convective boundary layer to study plume dispersion from an elevated pollution source. DiCristofaro (1980) examined their results in conjunction with surface heat flux measurements made over St. Louis and over Clarksville, TN to determine how a plume will be affected by turbulent mixing in the boundary layer for different surface heat flux values appropriate to real land use types.

We see from Figure 3, that the variation of surface heat flux over an urban area on a summer day is considerable. Highest values near the time of maximum heat flux occurred over the business and industrial parts of the city ($\sim$ 200 Wm^{-2}), while values of about 50 Wm^{-2} corresponded to areas of dense vegetation outside the city. In the vicinity of Clarksville, TN, area surface heat fluxes (Fig. 6) were generally low except over local urban centers.

DiCristofaro treated four heat flux values, 200, 100, 50 and 10 Wm^{-2}, which we consider to represent four different

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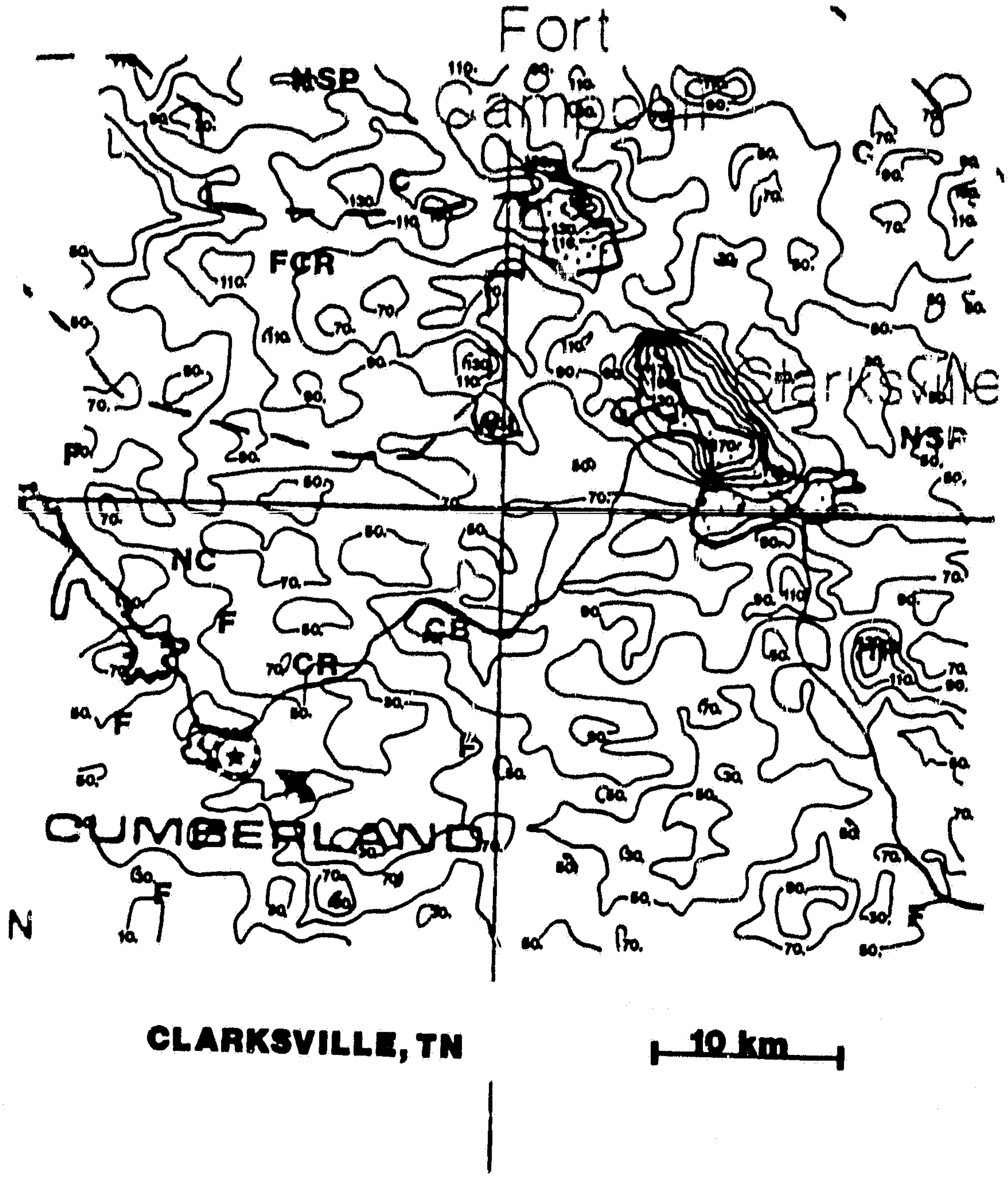

Fig. 6. Surface heat fluxes over the Clarksville, TN area, 22 August 1978 at about 1330 LST. Values are in Wm^{-2}. (From DiCristofaro, 1980)

land use types: an urban center, a suburban area, a densely vegetated canopy, and cool water, respectively. Not surprisingly, he found that the plume spread, both vertically and horizontally, would be significantly greater over an urban area, where there is greater mixing during the day. However, the mean concentration of pollutants at any point would be lower over the region of greater surface heat flux due to the more rapid spreading of the plume.

One unexpected result of this study was obtained, which is illustrated in Fig. 7.. For a given pollution source strength, Willis and Deardorff's (1978) curves indicate that the highest mean ground level point concentration ($\overline{\chi}(x,0)$ at a distance x downwind of the source is independent of the surface heat flux, although the distance at which the plume reaches the surface (the location of the maximum surface concentrations in Fig. 7) appears to decrease with increasing surface heat flux. A plume, therefore, disperses more rapidly but reaches the ground closer to the source when the heat flux is large. It is evident that in the design of power plants, consideration must be given to the land use downwind of the site. An urban area will produce higher heat flux values which lead to higher concentrations of pollution being deposited nearer the site. Lesser amounts will be deposited at greater distances from the site than if a site is located upwind of a forest, for example. It would appear that satellite-derived heat flux measurements may aid in evaluating the nature of land

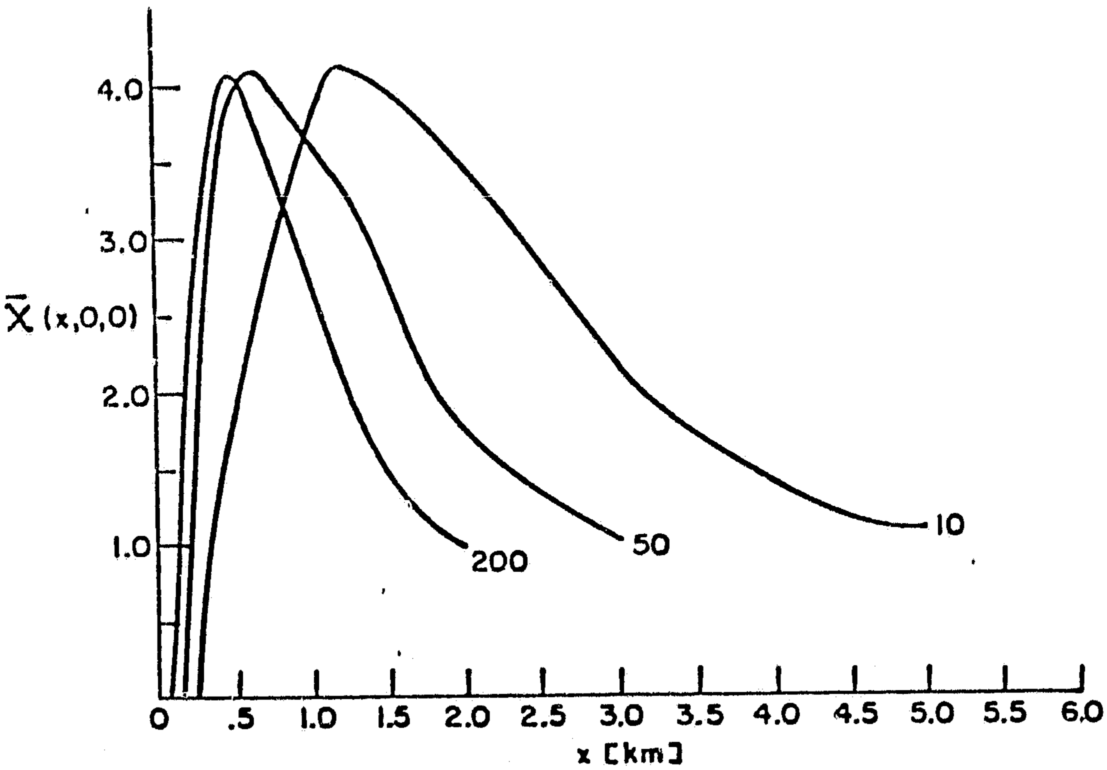

Figure 7. The mean ground-level point concentration ($\overline{\chi}(x,0)$) as a function of the downstream distance from the source for H_o=200, 50, and 10 Wm^{-2}. (From DiCristofaro, 1980)

use in affecting plume dispersion from a power plant or other elevated sources of pollutants.

3.4 Model Development and Verification

If the surface heat flux and moisture availability derived from our method are ever to be utilized as practical or in an operational sense, their value will depend, in part, upon the confidence one places in the accuracy of the results. Consequently, it is more important at this time, having achieved an operational potential, to obtain some sort of independent verification of the method. This verification can be accomplished by measuring surface heat flux or evaporation or soil moisture independently, and comparing those values with the equivalent model parameters derived from an analysis of remotely determined surface temperature measurements. A problem arises, however, in obtaining synchronous independent heat flux or evaporation measurements.

One set of independent surface layer heat and evaporation fluxes were obtained in the vicinity of the Clarksville, TN area during the sulfur transport and transformation in the environment (STATE) experiment conducted during August 1978 (Schiermeier *et al*, 1979). Several land use flights were made by a NOAA aircraft during the period for the purpose of measuring vertical heat and moisture fluxes using the eddy correlation technique[1]. Unfortunately, only one HCMM day/night image pair was made during the STATE experiment (Aug. 22), and the orbits occurred on a day that did not coincide with any aircraft boundary layer flux measurements. Nevertheless, we have noted that patterns of surface fluxes and moisture availability tend to remain unchanged in time because they are principally determined by land use. Therefore, we felt that the few days separating the aircraft flux measurements and the HCMM overpass would not be a serious factor in comparing satellite derived patterns those derived from aircraft measurements.

After making an adjustment to the aircraft fluxes for altitude and time in order that they correspond with the surface fluxes derived from HCMM, DiCristofaro found that agreement between the two types of measurement was reasonably good for the evaporative fluxes but was relatively poor for the heat fluxes, the aircraft values being several times larger than those derived from the satellite measurements. Although we suspect that our heat flux values were a little too low, the aircraft values seem much too high. Moreover, the aircraft heat fluxes were larger over a relatively cool forested area than those measured over warmer surfaces, a situation that would appear to be contrary to physical reasoning. Thus, the results of these comparisons appear to be inconclusive.

[1]J. Ching, Environmental Protection Agency, private communication. Unpublished report entitled "Turbulence studies; data report for the airborne turbulence data".

A second attempt at model verification was made during the summer of 1980 in the form of a small field experiment which was conducted over a cropland site several miles from the Penn State Campus. The site was chosen because it was also the location of the department's acoustic radar sounder. It is possible, given the proper calibrations for the sounder, to determine the surface heat flux during free convection conditions from the sounder data (Brown and Hall, 1978). This is done by determining a structure function C_T, which is a measure of the reflectity variations received by the sounder. Theory states that heat flux at the surface obeys a 4/3 power law between height and C_T^2.

Altogether seven experiments were made. On clear days the sounder was operated and the data recorded on tape. Satellite ground temperature measurements were simulated using a PRT-5 infrared radiometer loaned to us by EPA, which was operated by hand from a tower mounted atop of a mobile van at a level about 16 feet above the surface. The van was then moved to different locations around the sounder. Ground temperature measurements were made twice during a field operation, once during the early afternoon and again shortly after midnight, corresponding to the simulated times of the satellite overflights. On one of the afternoons, the ground-based surface temperature measurements were supplemented by additional radiometeric data collected with a hand-held radiometer carried on board a small aircraft which was flown over the site. Results of the verification study are not yet analyzed but a full discussion will appear in Cooper's thesis, due to be submitted in the winter.

3.5 System Development

The main thrust of our present systems work is in converting our analysis package, previously operating on the IBM-370, to the department's minicomputer and image processor facility. This phase of the work was completed last spring. Currently, we have the capability of performing all the data analysis interactively on the minicomputer. We are moving now toward a total operation in which both analyses and model operations are no longer performed in batch processing on the IBM but are carried out interactively on the minicomputer system.

The greater flexibility offered by the interactive image processing is illustrated in Fig. 8 where the three panels from top to bottom contain successive enlargements of the original image area on the HCMM tape. In this case, the Washington, D.C. heat island, the focal of attention, was enlarged to finally obtain the 128 x 128 working area (bottom panel).[2] After the working area was obtained, ground control points were found by setting the cross lines on a particular terrain feature and placing a command to print out the image coordinates of that

[2]The working area is 128 x 128 pixels on the minicomputer but 130 x 130 pixels on the IBM computer.

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Fig. 8. Successive enlargement of Washington, DC heat island for HCMM nighttime infrared image, 11 June 1978, approximately 0230 LST (white represents warmer temperatures, white warmer temperatures). The top picture contains almost the full HCMM image. The lowest panel contains the 128 x 128 pixel working area.

feature. Subsequently, the working image was stored and the control points used to determine the location of the image area within a set of fixed map coordinates. Originally, these operations required at least several days to accomplish on the IBM-370. Now, this aspect of the image processing can be accomplished in a couple of hours. Histograms of the intensity values within the working area can be obtained. A 'cloud removal' scheme also exists for cleaning up images contaminated by small amounts of cloud. Once a day/night image pair is stored on disk, the boundary layer model can be executed.

We are now concentrating on converting the boundary layer model to the minicomputer system in order to make the model a part of the minicomputer job stream. In order to allow the model to be viable on the small computer, we are spending some time increasing the speed and reducing the storage requirements of the model. As a result, the model now uses about 20,000 bytes of storage and executes a complete cycle of 22 hours model time in only a few seconds. This aspect of our research is being conducted by Arthur Polansky, a graduate student in meteorology and computer science. His thesis on this problem will be finished by Spring, 1981.

Further system development has proceeded with the building of local graphics capability on the department's flatbed plotter. We anticipate that by summer 1981 the entire analysis sequence, as summarized in Fig. 1, will be operational on the minicomputer facility.

In order to test our interactive facilities, we performed a preliminary set of analyses on one HCMM image for Central Pennsylvania. Largely because of local interest in the subject, we were interested in analyzing the nighttime temperatures over the Pennsylvania Barrens, which is a region where anomalously cold temperatures occur on clear nights (Schlegel and Butch, 1980). Our analysis, showing near freezing temperatures at 2:30 AM LST on 11 June 1978, are discussed in Appendix III. Analyses for Washington, D.C. shown in Appendix II, were also performed on the interactive system.

3.6 Error estimates: the uncertainty in determining surface heat flux

It should be pointed out that an offset correction of 5.0^{o}C, approximately that recommended by NASA, was applied to all temperature data except for those of St. Louis and Los Angeles shown by Dodd (1979) and for those of Goodwater Creek area by Kocin (1979). Temperature corrections for atmospheric water vapor absorption were made for all cases, however, using various methods such as that of Cogan and Willand (1976) for the Dodd and Kocin cases. For later cases, we used a radiation model originally provided by NASA. That radiation model was later found to contain an incorrect representation for water vapor absorption. A revised version, described by Barnes and Price (1980), was issued. The revised NASA model arrived too late to make any corrections. However, we did perform a series of comparisons showing that the differences between the old and new NASA models were small for our particular case studies. In assessing our completed analyses we recommend that a correction be made to all the temperatures of the various case studies that we published. For the Dodd and Kocin results, including those of Carlson et al. (1981), 6°C should be added to daytime temperatures and 4°C to nighttime temperatures. Consequently, the published heat flux and thermal inertia values for those cases are probably somewhat too low while M and the evaporative fluxes are likely to be too high. For later analyses, such as those of DiCristofaro and the Washington, D.C. case study, a correction of 1°C should be added to the daytime temperatures but no correction need be made to the nighttime values.

In considering all sources of error and uncertainty in the satellite measurements, we do not feel that measured ground temperatures are likely to be correct to within ± 1-2°C. The greatest source of measurement error arises from the choice of a uniform ground emissivity and from a neglect of near-surface atmospheric temperature and moisture distribution in making water vapor absorption corrections.[3]

Since 1-2°C is also considered to be an upper limit to the measurement accuracy of the model itself, efforts to refine the boundary layer model might be fruitless in view of the various limitations imposed by a measurement accuracy. However, if one

[3]This error may not be trival but is unavoidable unless one wishes to consider the temperature and dewpoint distribution over the lowest few meters or centimeters above the ground. Such a refined vertical stratification is seldom considered in radiation models.

is willing to accept such uncertainties in both measurement and models, realizing that subsequent errors in determining the surface fluxes will not be great, one can ignore various troublesome theoretical inconsistencies because individually such errors produce computational uncertainties no greater than those which arise from the measurements themselves.

4. Summary and Conclusions

It is useful to separate our achievements into two categories (1) developmental and (2) basic science. In the first group we refer to advances made by combining existing theory with standard operational capability to obtain analyses or products that are unique. The second category, that of basic science, pertains to interpretation of results from which the processes of nature can be illuminated to arrive at a new view of how these processes operate.

4.1 Developmental

We now summarize our principle achievements in the use of image processing techniques.

- We have been the first to use satellite imagery to obtain maps of the surface energy budget, moisture availability and thermal inertia.

- We were also the first to describe the urban heat island using satellite data.

• We were also the first to use satellite data in conjunction with theory to examine processes in the boundary layer.

• We will shortly have the capability of performing these analyses interactively.

• We brought to the attention of numerical modelers the practicality of determining various surface parameters using satellite temperatures. These surface parameters govern the surface heat flux which we have shown to possess a large horizontal variability. Thus, the thermal forcing of atmosphere circulations by differential surface heating can be analyzed with the aid of satellite data.

• Our research has led us to investigate three separate, but related, topics:

a) the urban heat island

b) evaporation over vegetated surfaces

c) effect of variable heat flux on power plant plume behavior

• Theoretical advances in modeling have been slow. Further improvements must await the results and evaluation of verification studies.

4.2 Scientific

We now list the main scientific conclusions of our HCMM research.

• Surface heat flux during periods of free convection (clear skies, strong insolation) closely resembles the distribution of afternoon temperature, higher temperature where there is greater heat flux.

• Heat flux varies in the opposite sense of evaporation. Relatively warm temperatures and higher heat flux correspond to lower evaporation.

• Over heterogeneous regions such as cities, land-use (specifically vegetation cover) governs the temperature pattern. The less vegetated and the more industrialized and commercialized surface are associated with a greater heat flux. Evaporation, nevertheless, appears significant over urban centers, as recently founded by Kalanda et al. (1980).

• Over vegetated surfaces the Bowen ratio (H_o/E_o) is small, usually about 0.1 - 0.2 over forests or mature cropland. There is some evidence that the evaporation varies with local rainfall. Importantly, this would suggest the satellite as a useful tool in the determination of evaporation and soil moisture.

• Because of their greater thermal inertia and ability to transpirate freely, forests appear relatively cool during the day and have low Bowen ratios but they are relatively warm at night. Consequently, wooded mountains, such as those found over central Pennsylvania, can be warmer at night than the more open valleys.

• The nocturnal urban heat island, at least during summer, may be due more to the enhanced heat storage during the day than to a greater ability of the urban substrate to store and transmit heat. If so, the nocturnal heat island can also be attributed to the distribution of non-transpirating surfaces and the absence of vegetation. Vegetation, in fact, may be the largest determinant of surface evaporation patterns.

• Dispersion of pollutants emitted in the form of plumes from power plants is dependent upon the surface heat flux downwind of the site. Plume spread is therefore dependent upon the nature of the surface fabric. Over surfaces having a relatively large heat flux, the plume is dispersed more readily but the maximum surface pollutant concentrations occur closer to the source. Curiously, the maximum pollutant concentration at the surface does not appear to be dependent on surface heat flux.

4.3 Problems and Recommendations

Currently, we feel that the greatest task in establishing the utility of satellite data for numerical modeling or soil moisture analysis lies in assessing the accuracy of the model used to transform the temperature measurements to surface heat flux or evaporation. Part of the verification problem arises from the fact that a model is an idealized system with an idealized physical structure. In practice, the surface canopy is highly complex. The questions are (1) what is the appropriate surface temperature for determining the surface fluxes using a model and (2) is the radiometric surface temperature the correct one to use for these purposes?

There are many intractable aspects in using satellite radiometric measurements to determine surface heat flux and evaporation. Ultimately, the value of the satellite as an operational tool should not depend on the availability of special in-situ ground measurements. The use of remotely determined temperatures for inferring surface heat flux or evaporation or for obtaining the governing surface parameters will only be practical on a routine basis provided that all the data required for converting the temperatures to the other quantities can be obtained routinely, by satellite and conventional meteorological observations. It remains to be seen whether such a capability for obtaining operational surface flux measurements can be achieved.

In the end, however, the determination of surface heat flux or evaporation by satellite using infrared surface temperatures may not be feasible except within rather broad limits. However, our present model does appear to yield reasonable results. For example, evaporation values are close to the maximum (the potential evaporation) over densely vegetated surfaces or water and are small over very dry surfaces; commonly heat fluxes are found to be large over dry surfaces and small over wet surfaces. A modest degree of resolution in calculating heat flux may be the best that one can expect to achieve although an ability to distinguish dry from moist and highly conducting from poorly conducting surfaces is, nevertheless, of some practical value for numerical modeling and for land use studies. Much remains to be learned from the use of our method. For example, we would like to see if the distribution of surface heat flux, moisture availability and thermal inertia, are as variable on the larger scale as they are over cities, and whether this larger scale variation can be put to practical use in atmospheric prediction models.

4.3 Recommendations for future satellite programs

Besides the uncertainties in data interpretation and theory, a major impediment to the practical application of satellite data is its lack of availability. We feel that HCMM data was extremely good quality, despite problems in ground truth calibrations and uncertainties in how to apply the moisture correction. The high resolution of the satellite reliability of the data, and the relative ease in which the data format enabled working scientists to read the computer compatible tapes were exemplary. However, we can not too strongly urge that future satellites of this type be scheduled in such a way as to allow for nearly daily coverage of day/night image pairs at any given point over the United States. We feel that the 16 day recurrence cycle of 12 hour day/night image pairs all but eliminated any chance for studying time time rate changes at the surface. Because of cloud cover, we were unable to obtain any 36 hour image pairs for Houston, TX. Moreover, we were able to obtain only a few usable 12 hour image pairs for Washington, DC or St. Louis, MO.

Therefore, we would suggest that daily recurrance of 12 hour images be made an important requirement in future scheduling of satellites, even if the surface resolution would have to be decreased. The capability for measurement in both visible and infrared channels and for obtaining 12 hour image pairs at times shortly after noon and mid-night were uniquely useful features which should be retained. We cannot stress too highly the advantage of having day/night thermal images at times close to the maximum and minimum temperature. Easier access by the user to the data processing machinery should be encouraged in order to enable scientists to plan and carry out synchronous field operations in conjunction with favorable satellite orbits.

At present there are virtually no operational satellites in existence that can provide useful, high resolution temperature information on a 12 hour sequence close to the times of maximum and minimum temperatures. TIROS-N and its successor, as well as HCMM, are dead. Consequently, uses of satellite measurements in determing surface evaporation, in acquiring data bases for numerical models and in analyzing land use are limited. We, therefore, strongly urge that a new series of HCMM satellites be designed and launched but that future applications be tempered by scientific results from the analyses of existing satellite data.

Appendix I

A.1 The Carlson Method for Inferring Surface Parameters from Ground Temperature Measurements.

We have developed a rather detailed one-dimensional model capable of predicting the surface temperature and surface energy balance from a set of initial conditions. Used in conjunction with measurements of ground temperature, the model can be inverted to yield estimates of two surface parameters, the moisture availability and the thermal inertia, as well as the surface energy budget. The Carlson method, henceforth referred to as CM, has been used to infer patterns of moisture availability over urban and rural areas. In Figure 4 the moisture availability distribution is shown for the Goodwater Creek Watershed. In CM, the moisture availability (M) is the ratio of evaporation to potential evaporation. Over vegetation surfaces, this parameter may be correlated with rainfall amounts (Fig. 5) as well as with vegetation types. Over variable ground covering, M is sensitive to the amount of vegetation, being high (0.7 to 0.9) over densely vegetated surfaces and low (0.1 to 0.4) over urban centers.

Much of our analyses work is now being carried out interactively using the Penn State minicomputer and image processing facility. We now possess the capability for manipulating images from satellite data tapes and displaying those images on a monitor. This procedure allows us great flexibility and facilitates the procedure for extracting patterns of evaporation and moisture availability. As Carlson and Boland (1978) have shown, such patterns can be obtained provided that two surface temperature images are supplied, preferably for times close to the maximum and minimum temperature.

A.1.1 The Carlson Model

The CM model can be called a predictive combination model because the temperature in the ground and in the air are predicted from a set of initial conditions, as are the moisture and wind speed in the atmospheric surface layer. The term combination arises from the fact that the model combines a surface energy balance with the vertical flux equations. At the surface, the energy budget is written

$$R_n = H_o + L_e E_o + G_o \tag{A.1}$$

and the flux equations are

$$H_o = \frac{\rho C_p (T_o - T_a)}{r_a + r_{ch}} \tag{A.2}$$

$$E_o = \frac{\rho (q_o(T_o) - q_a)}{r_a + r_{cv}} \cdot M \tag{A.3}$$

where R_n is the net radiation, $L_e E_o$ and H_o the evaporation and sensible heat fluxes at the surface, G_o the heat flux into the substrate or canopy, ρ the air density, T_o (q_o) surface canopy temperature (surface humidity), T_a (q_a) the air temperature (specific humidity) and r_a, r_{ch} and r_{cv} are, respectively, the bulk air resistance, and the canopy-air transition layer resistances for heat and water vapor. These equations are expressed in the resistance terminology used by many plant scientists (e.g., Monteith, 1975). Carlson and Boland (1978) make use of a <u>moisture availability</u> M, where $M \equiv \frac{r_B}{r_B + r_s}$ accounts in bare soil for the efficiency of evaporation and $r_B \equiv r_a + r_{cv}$. Generally, M represents the fraction of <u>potential evaporation</u> E_o/E_p. For bare soils r_s is probably a function of soil water potential ψ_s or the fraction of field saturation for the medium; for plants it represents a <u>stomatal</u> resistance which is only loosely coupled with the soil moisture. Under moist conditions r_s is essentially zero and the evaporation is virtually equal to the potential value. Under drying conditions M decreases, r_s increases, and the evapotranspiration is controlled by the water potential in the soil or by the stomatal closure in the leaves.

The energy budget formulation subscribes to one assumption that seems to be well substantiated: that evapotranspiration is limited by the availability of net radiation, subject to the partition of the radiation into heat flux and substrate storage. (Under conditions of strong advection, this condition of balance needs some alteration).

Substrate storage is handled thusly: at the surface

$$G_o = \lambda(o) \left.\frac{\partial T}{\partial z}\right)_{z=0} \qquad \text{(A-4)}$$

and below the surface

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \kappa(z) \frac{\partial T}{\partial z} \tag{A.5}$$

where λ is the canopy conductivity at z=o and $\kappa(z)$ is the diffusivity of the substrate medium. The ratio $\lambda/\kappa^{1/2}$ is called the <u>thermal inertia</u> (P) and most models that utilize the thermal inertia approach currently assume that κ is not a function of depth. Although it would seem from equations (A.4) and (A.5) that there are two independent variables, λ and κ, Carlson and Boland (1978) emphasize that these parameters can be varied independently and the same results produced provided that P is held constant from one model experiment to another. The thermal inertia approach is quite valid for bare soils or closely cropped vegetation but may be unsatisfactory for deep vegetation canopies.

In CM, the surface temperatures are determined as an equilibrium value, a solution for the five unknowns, H_o, E_o, T_o, G_o and substrate temperatures are obtained from an interative solution of the five equations A.1 through A.5. Evaporation or evapotranspiration values are obtained by matching <u>measured</u> satellite surface temperatures against the <u>predicted</u> temperatures generated from a set of model runs. The method for obtaining the surface fluxes and terrain parameters using the model and given t e surface temperature measurements is illustrated schematically in Fig. 1.

Carlson and Boland (1978) show that the two parameters M and P are the most important in determining the surface energy fluxes and surface temperature variation in a model and that, given estimates of the remaining parameters from routine conventional measurements, the surface temperature T_o or heat flux H_o can be determined to an uncertainty of less than $\pm$ 2°C and $\pm$ 20%, respectively (section 3.6). The CM incorporates the essentials of the diagnostic models but contains additional prediction equations governing the air and substrate properties. Inclusion of the energy balance places restraints on the availability of energy and on the partition of energy into the various fluxes, thus assuring an internally consistant result which is not dependent on the continuous in-situ measurement of air or substrate temperature. Nighttime temperatures are also computed in a similar manner, although atmospheric fluxes usually vanish under stable conditions.

Two predictive models have been developed in Europe which are very similar in structure and usage to the CM. One is called the Tell-us model (Rosema, 1979) and the other, the Tergra model (Soer, 1980). Although the Tergra model has been designed specifically for vegetated surfaces, both the Tergra model and the CM make use of the diffusion equation (A.5) for storing heat in the substrate, although in the Tell-us model the surface heat flux is made an arbitrary fraction of the net radiation for a crop-covered surface. The Tergra model, like the CM, contains a near-surface transitional layer between the crop or ground surface and the surface air layer. However, the CM, unlike the European models, accounts for the change in wind with time above the surface during stable conditions.

One defect that such models suffer from is their treatment of the microstructure of the vegetation canopy, specifically the way in which heat is transported to the earth's surface through the canopy. Although the thermal inertia approach of allowing the surface canopy to diffuse heat through it may yet prove to yield reasonable results in the model, the formulation for vegetation remains somewhat crude or artificial in both the CM and the European models. Deardorff (1978) has attempted to construct an elaborate framework for inclusion of a layer of vegetation but such specific formulations also suffer from being highly unrepresentative of any particular vegetation canopy. Shuttleworth (1976) deals with the issue by discussing a general formalism for inclusion of a vegetation canopy and Perrier (1979) discusses the complex behavior of wind and temperature in a canopy, showing that the profiles of these meteorological variables depend intimately, and perhaps intractably, upon the density and type of vegetation surface. Improvement of the canopy parameterization is of primary interest to our soil moisture work.

A.1.2 Virtues and Limitations of the CM

At present we feel that the CM offers the following advantages for determining regional scale evaporation:

a. It requires a minimum of external parameters. Those required such as wind speed or air temperature can be set as initial conditions and are obtainable generally from routine sources. Continuous in-situ monitoring at the microclimate is thus unnecessary.

b. The method is readily adaptable to regional scale (10s to 100s of kilometers on a side) analyses of satellite information

c. It incorporates a detailed formulation of boundary layer physics.

The model also possesses some disadvantages:

a. It is probably deficient over some types of vegetation, notably, densely-covered surfaces. Thus, it may incorrectly predict a substrate temperature when the structure of the vegetation cover should be accounted for. Improvement of the vegetation formulation in CM is imperative.

b. Like all one-dimensional models, it suffers from neglect of regional scale and local advection.

c. It does not handle cloud cover.

Appendix II

Analysis and interpretation of HCMM surface temperature patterns over Washington, D.C.

A study of the Washington, D.C.heat island was undertaken. The results have not been published in any document. Clear weather conditions occurred over the entire eastern seaboard during the period 10-12.1978. A day/night orbital pair of HCMM flights occurred over the Washington, D.C. area on 11 June 1978. The analyses of surface temperatures for the day (Fig. B-1) and night (Fig. (B-2) clearly reveal the urban heat island. At 1300 LST, the surface temperature over downtown Washington exceeded 36°C, while at night the temperature over the inner city was about 17 C. Over the outer suburbs, however, daytime and nighttime temperatures were about 28-30°C and 13-14°C, respectively. In accordance with these temperatures the heat fluxes (Fig. B-3) were over 175 Wm^{-2} over the downtown area and 75-95 Wm^{-2} over the suburbs. It can be seen in Fig. B-4 that evaporation varied in the opposite sense to that of heat flux, high values occurring over the suburbs and lower values over the city. Nevertheless, the Bowen ratio over the city was still below 1.0 (a relatively low value), and only about 0.15 over the outer suburbs. Although we suspect that the heat flux values yielded by our method may be somewhat low, the overall pattern appears reasonable. The moisture availability distribution (Fig. B-5) reflects the pattern of heat flux. However, thermal inertia (Fig. B-6) was rather ill-defined, with no distinct maximum over urban centers. As we have indicated,

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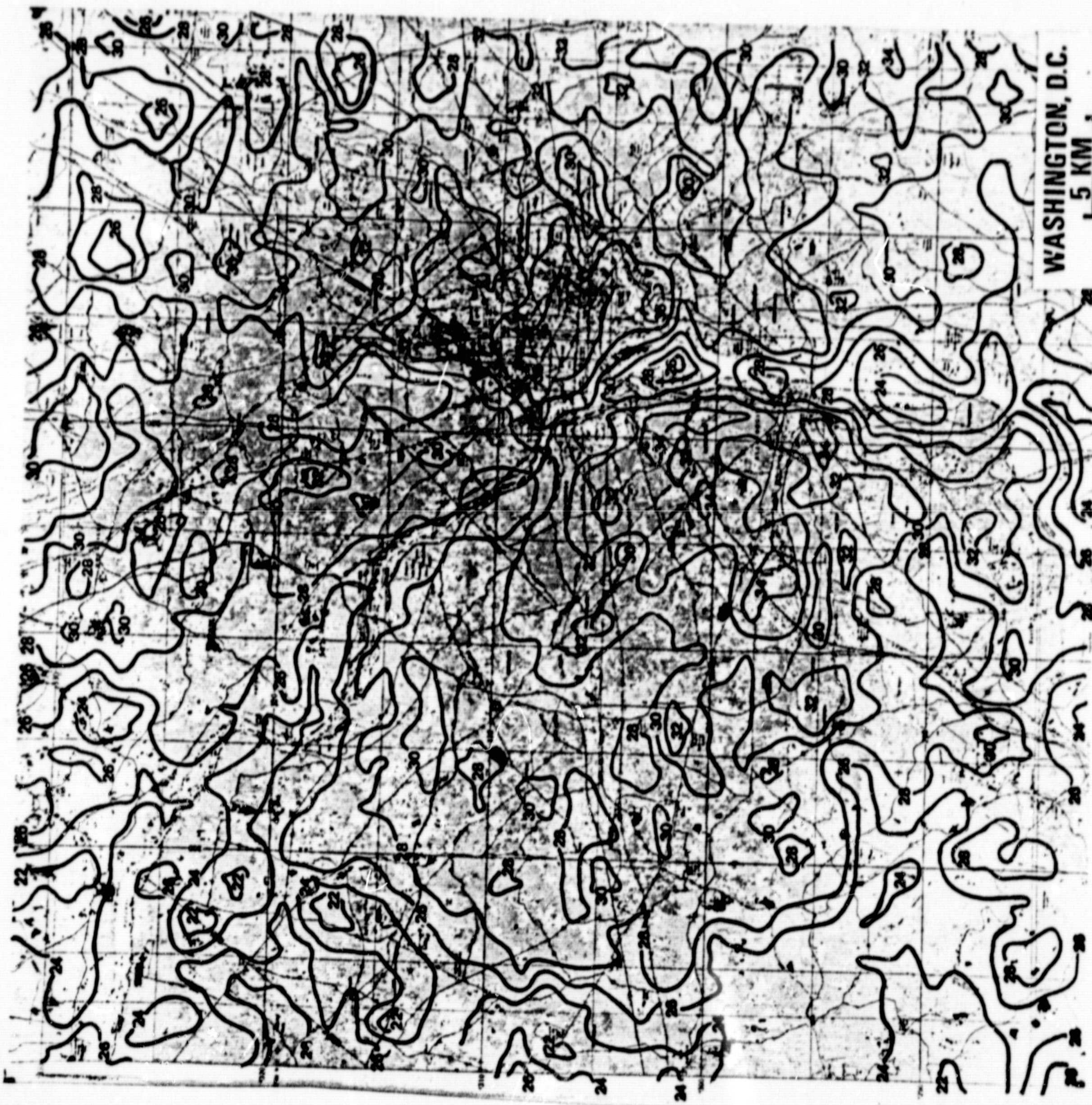

Fig. B-1. Surface temperature analysis (°C) over Washington, DC obtained from the HCMM satellite on 11 June 1978, approximately 1330 LST.

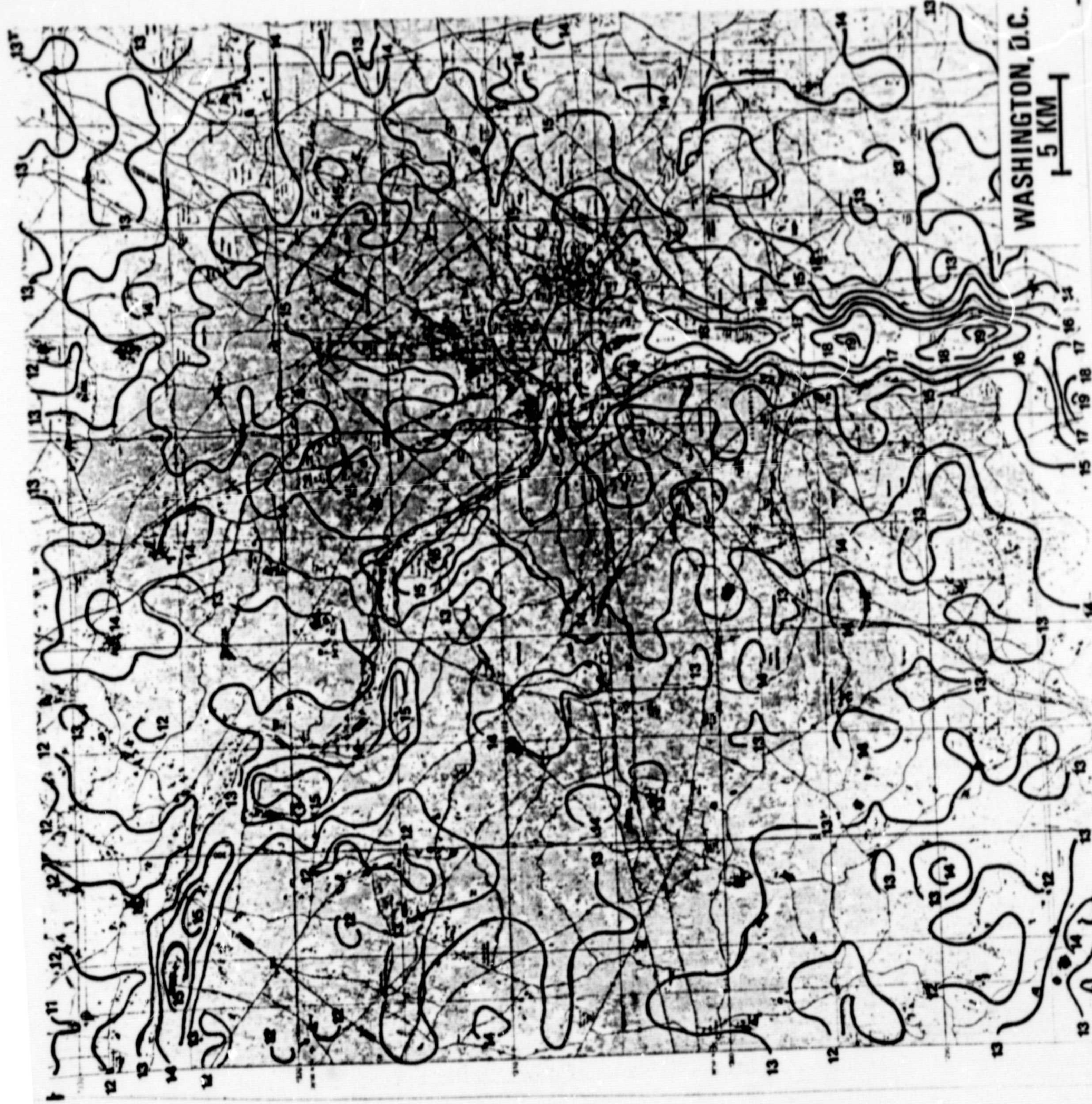

Fig. B-2. Same a Fig. B-1 but for the nighttime temperature analysis, approximately 0230 LST, 11 June 1978.

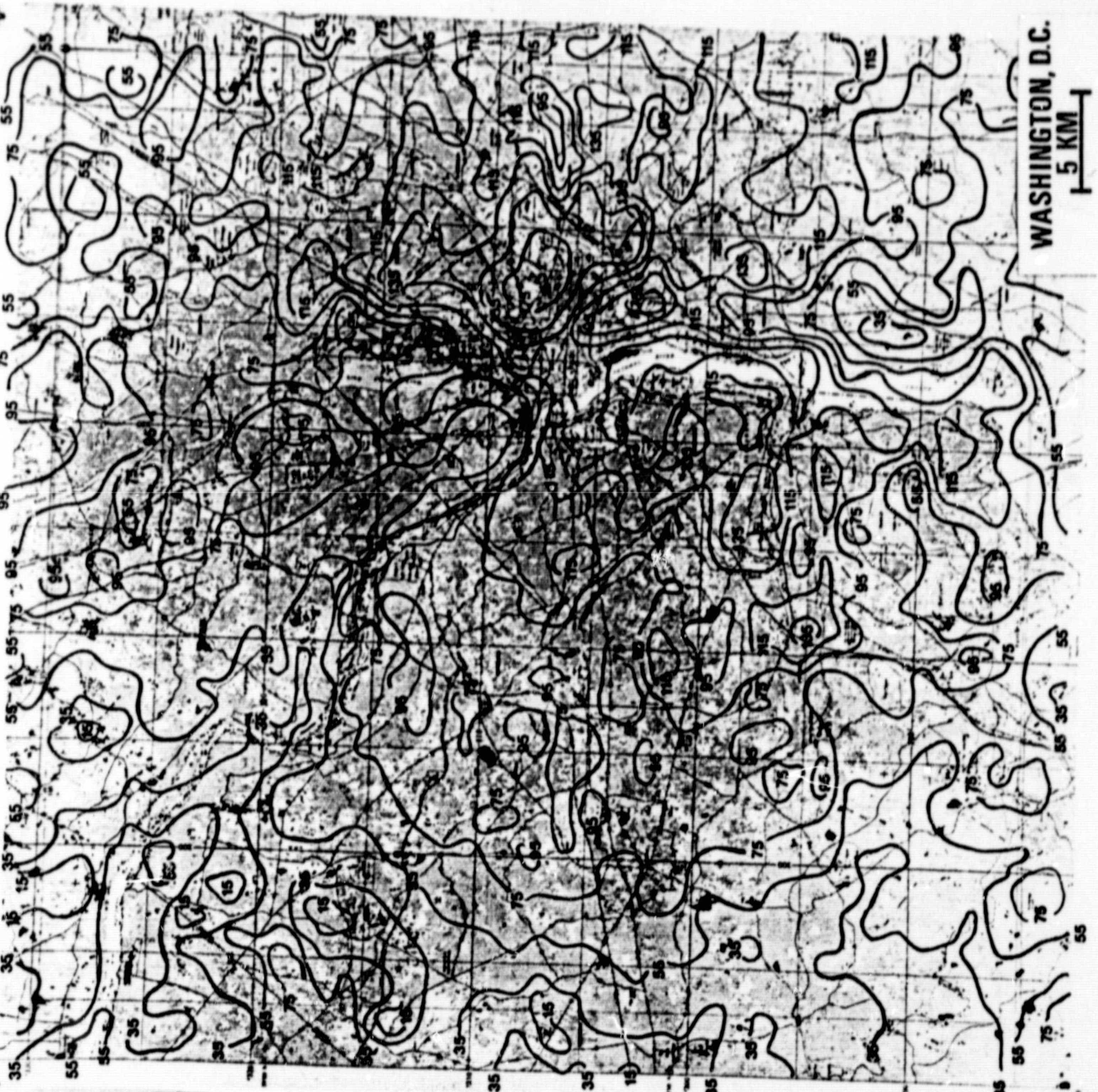

Fig. B-3. Same as Fig. B-1 but for surface heat fluxes in units Wm^{-2}.

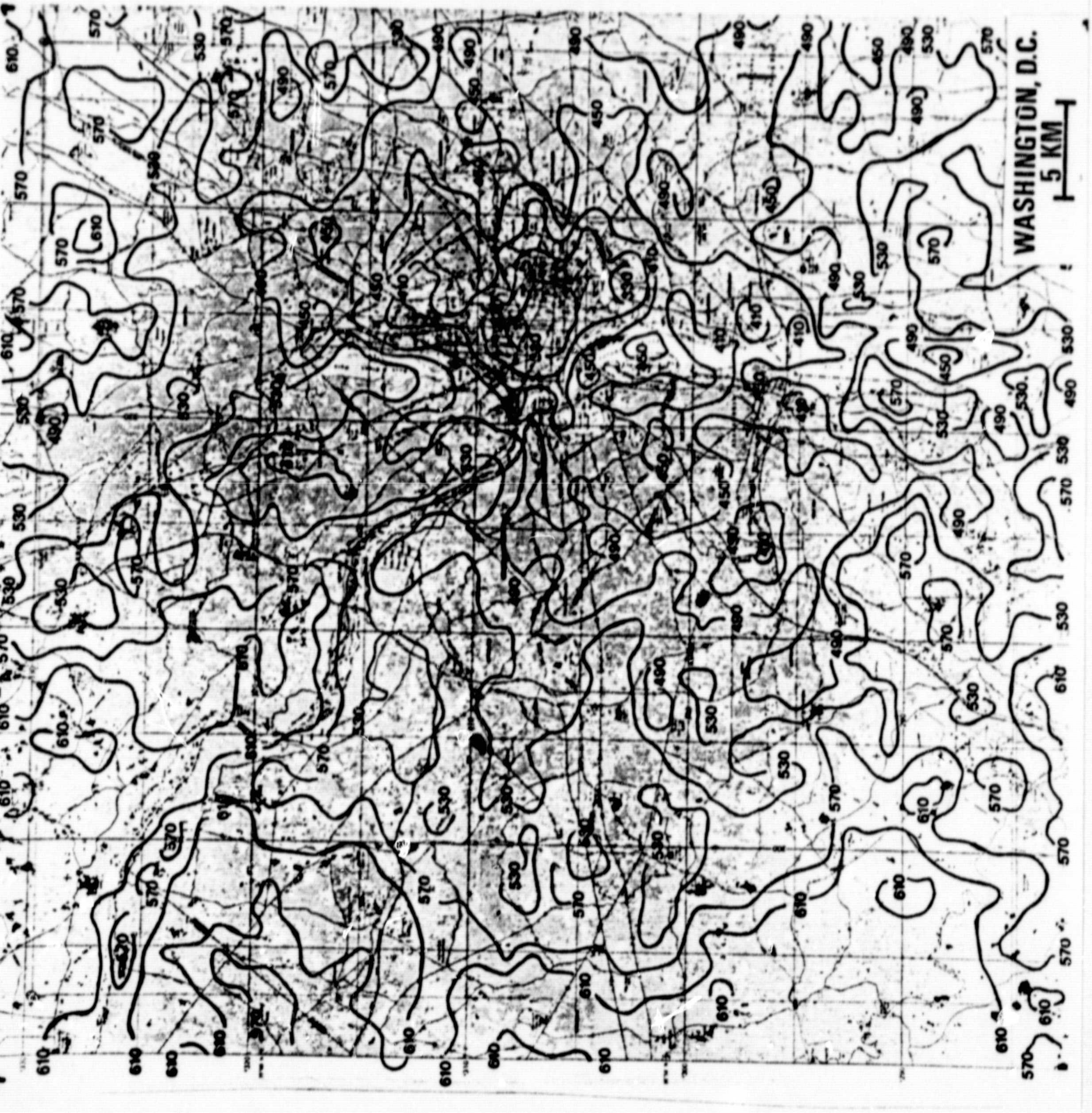

Fig. B-4. Same as Fig. B-1 but for evaporation fluxes.

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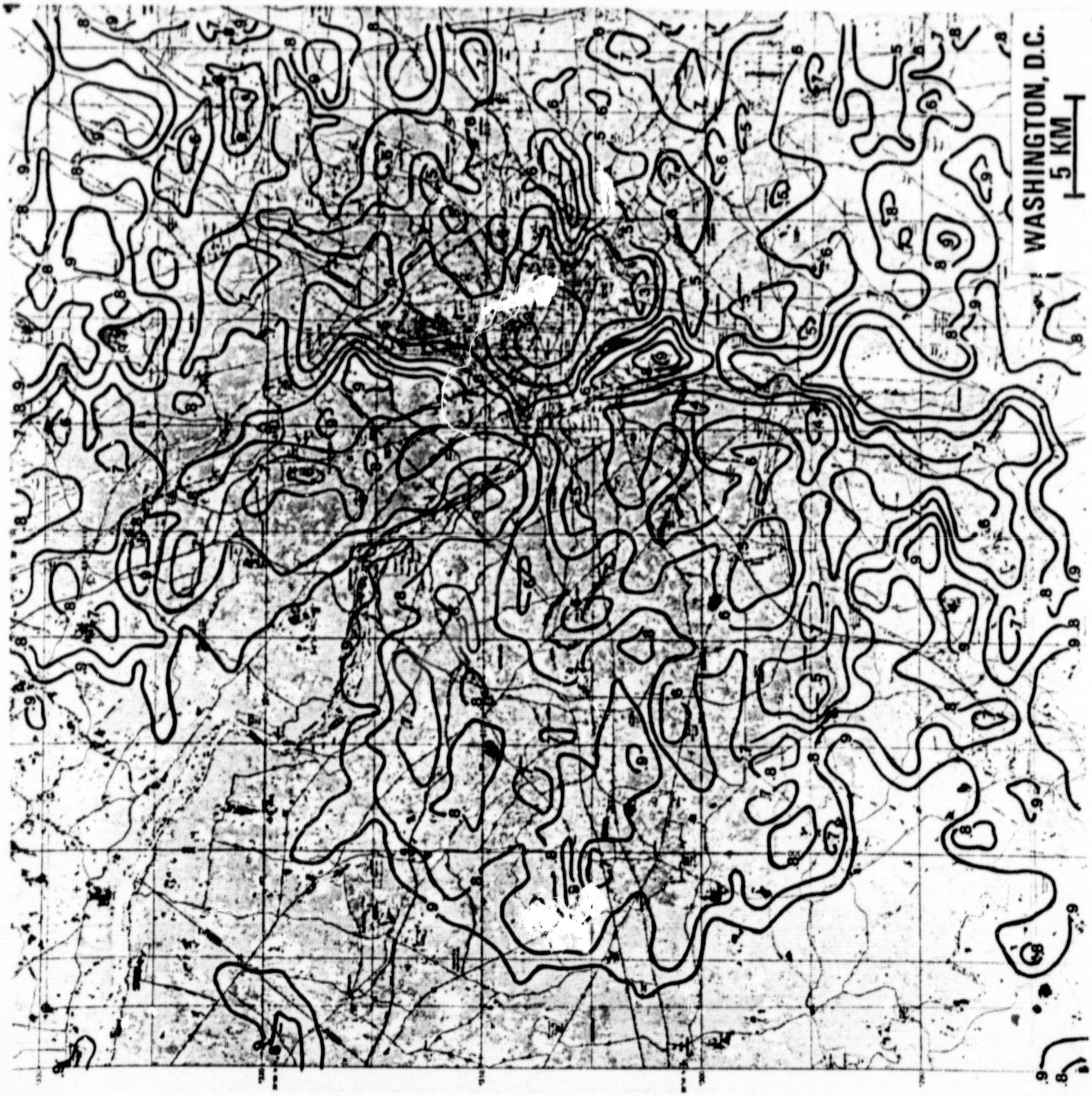

Fig. B-5. Same as Fig. B-1 but for moisture availability M.

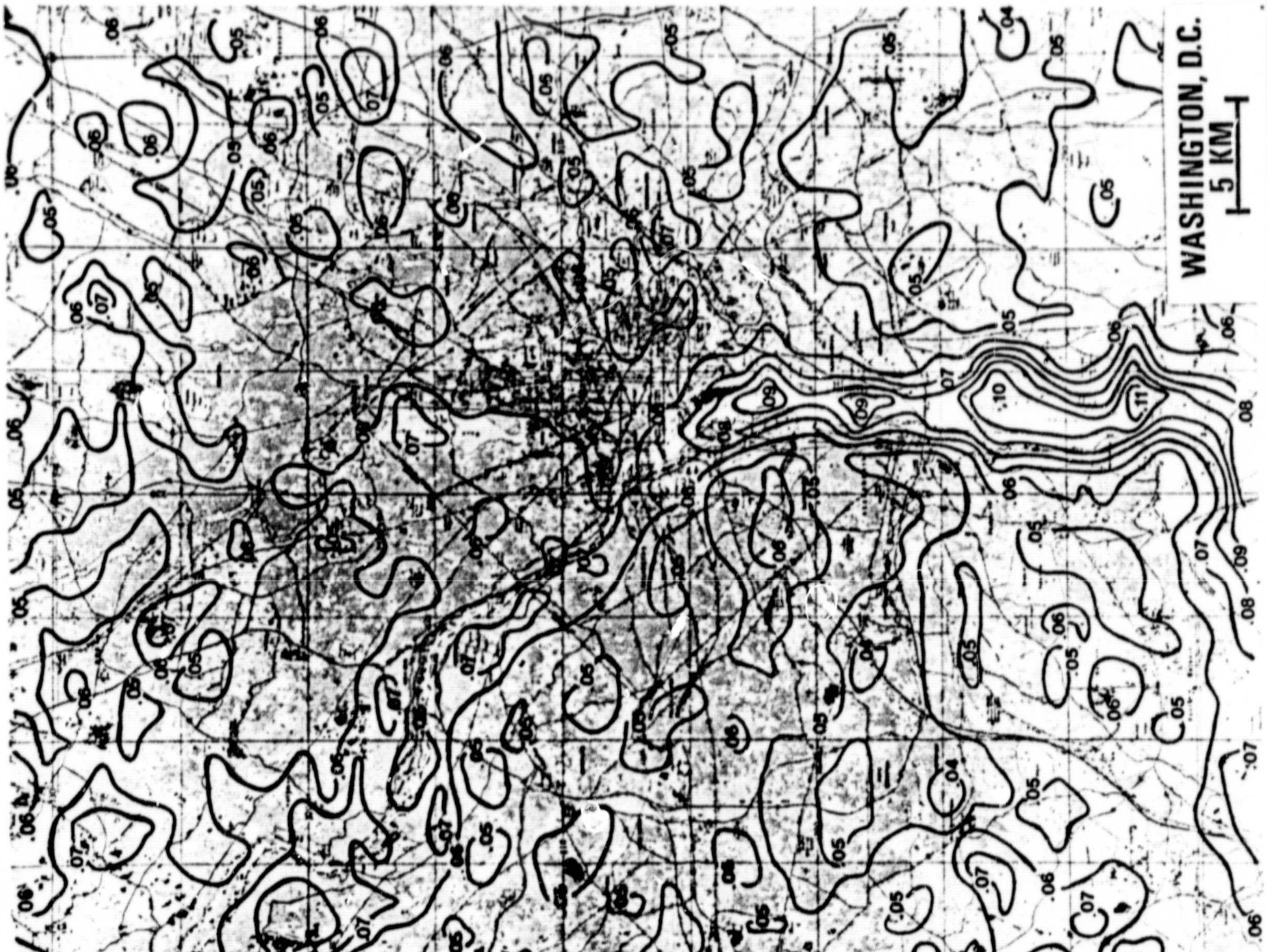

Fig. B-6. Same as Fig. B-1 but for thermal inertia P in units of cal $cm^{-2}K^{-1}sec^{-\frac{1}{2}}$ (note that approximately 400 TIU (400 $Wm^{-2}K^{-1}sec^{\frac{1}{2}}$) equals 0.01 cal cm^{-2} $K^{-1}sec^{-\frac{1}{2}}$.

the elevated nighttime temperatures over the city can be explained on the basis of greater daytime heating, rather than because of the greater conductivity of urban surfaces. It is not yet apparent how P varies with land use. We suspect that, like M, it reflects some aspects of the water content of the surface. Note that P appears to be very large (>0.1) over the Potomac river and also over wooded areas, such as near Reston (labelled R in Fig. B-6), where values were about 0.07-0.08. Cleared suburban (but not urban) regions and possibly unplowed fields of stubble or grass yield relatively lower P values (~0.05).

Appendix III

An analysis of the Barrens temperature

According to Schlegel and Butch (1980), the Barrens of Central Pennsylvania is an anomalous region which under the proper weather conditions can produce a sub-freezing temperature during every month of the year. During fall and winter and under clear sky and light wind conditions, the temperature of the Barrens can decrease by 10-15°C below that of State College in just a few hours after sunset. The micrometeorological factors that permit such cooling are very interesting. The anomalous cooling often results in low temperatures that are below those reported anywhere else in the state or nation. For these reasons, the Barrens has generated great local attention.

In view of this interest, we decided that the Barrens would make a good topic for a scientific display during the last Earth and Mineral Sciences Exposition (EMEX), an event which is sponsored by the College of Earth and Mineral Science. During EMEX the public was invited to attend an open house for the purpose of learning about research and teaching projects in the College. A HCMM exhibit was presented using our newly developed interactive facilities. A TV monitor was linked to an image processor and mini-computer in which was stored a temperature image of the Barrens areas. What the public could see was a video display of an image in black and white which was similar to the temperature analysis of Fig. C-1. Mt. Nittany (arrow labelled M) and other mountain ridges were relatively warm. These ridges are generally covered with a dense tree canopy consisting of both deciduous and coniferous types. State College (labelled S) also appears warm as do most urban centers. The Barrens (black dot identified by arrow lavelled B) was decidedly cold, however.

Fig. C-2 consists of an enlarged temperature analysis over the region enclosed by a black border in Fig. C-1. The distinct coldness of the Barrens is even more apparent in this figure. There appears to be two minima, one which was near the instrument shelter (~2.8°C) and another slightly farther south (~1.5°C). Since the instruments shelter is known to lie in the coldest part of the Barrens, it is likely that the presence of trees located close to the instrument shelter resulted in the satellite temperature being too high to represent a true ground temperature. It is quite likely, however, that the actual air temperature was very close to the ground temperature in view of Schlegel and Butch's (1980) finding that the Barrens temperature is usually isothermal with height over the lowest few meters of the atmosphere.

On 11 June, the measured screen-level air temperature at the instrument site was 0.6°C at 0530 LST (the minimum for the day) and was 1.6°C at the time of satellite overpass (0230 LST). Thus, we feel that the HCMM analysis closely approximated the true ground temperature over that region. This analysis will be submitted in a short article to the Bulletin of the American Meteorological Society as a follow-up article to that of Schlegel and Butch (1980; see Carlson, 1981).

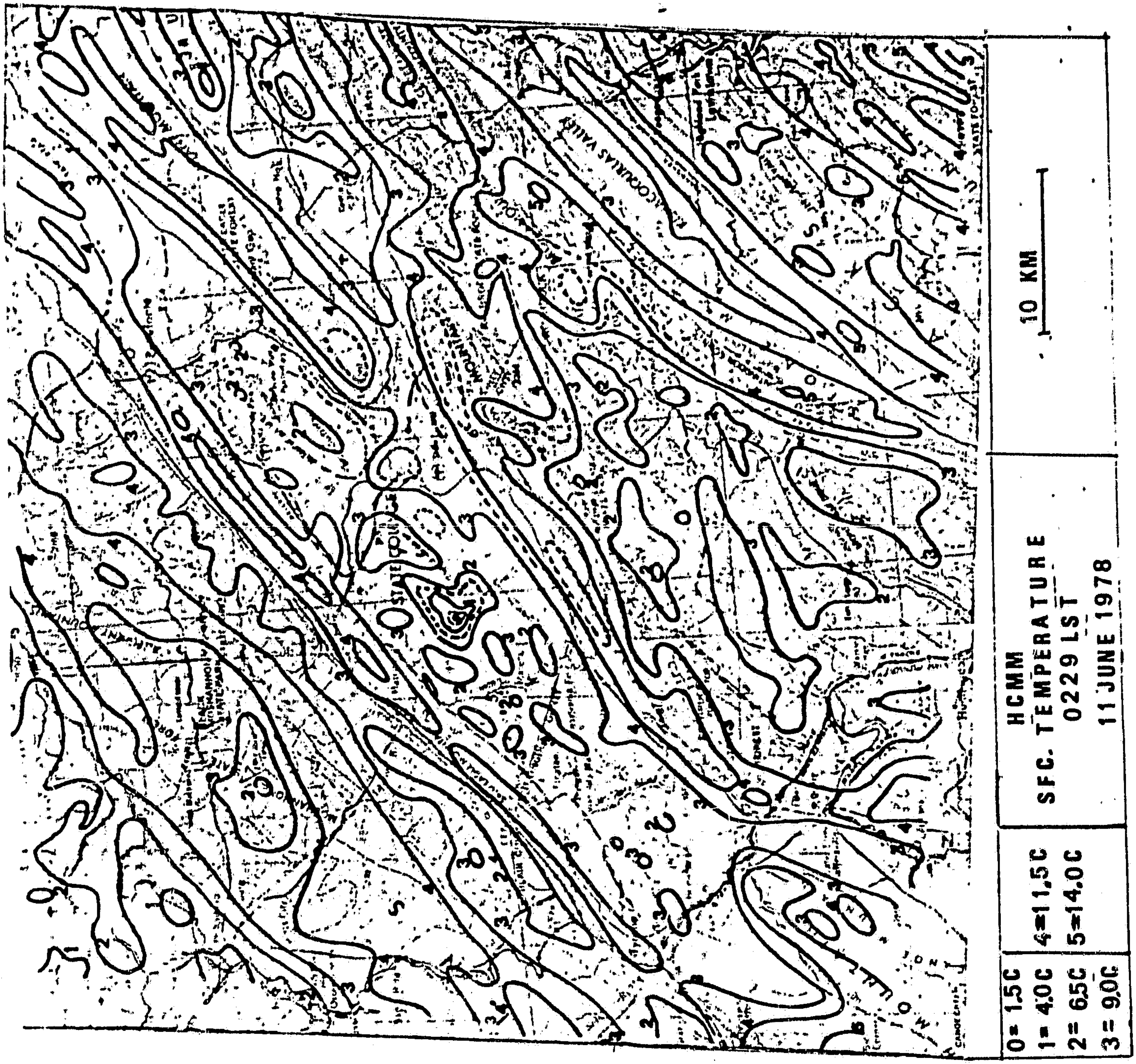

Fig. C-1. Temperature analysis over Pennsylvania, determined from HCMM measurements for 11 June 1978, approximately 0230 LST. Mt. Nittany is labelled M, State College with an S. The Barrens is located with a dot and labelled B.

Fig. C-2. Enlargement of the surface temperature analysis (^{o}C) over the Barrens region (enclosed by a border in Fig. C.1).

Appendix IV.

List of HCCM scenes for which analyses were performed on the computer compatible tape data.

Scene	Analysis area	Date	
A0045-19430-1,2	St. Louis, Goodwater Creek	day	June 10
A0044-08310-3	St. Louis, Goodwater Creek	night	June 10
A0035-213201,2	Los Angeles	day	May 31
A0034-10230-3	Los Angeles	night	May 30
A0046-07290-3	Washington, D.C. State College, PA (Barrens)	night	June 11
A046-182311,2	Washington, D.C.	day	June 11
A0156-6081603	Goodwater Creek	night	June 29
A0156-190901,2	Goodwater Creek	day	June 29
Ao119-082403	St. Louis	night	August 23
A0119-19701,2	St. Louis	day	August 23
A0118-185801,2	Clarksville	day	August 22
A0118-080703	Clarksville	night	August 22

CAPTIONS

Figure 1. Flow diagram for inferring model parameters (from Carlson et al., 1981).

Figure 2. Schematic diagram of the satellite data processing procedure (from Dodd, 1979). This sequence refers to the method of extracting satellite temperature images referred to in Fig. 1.

Figure 3. Surface heat fluxes over St. Louis, 23 August 1978 at about 1300 LST. Values are in Wm^{-2}. (From DiCristofaro, 1980).

Figure 4. Moisture availability M over the Goodwater Creek Watershed area (within dashed border), 9-10 June 1978, as dteremined from HCMM data from 36-hr pair of orbits. (From Kocin, 1979).

Figure 5. Rainfall amounts (inches) during the period 1-8 June 1978 over the Goodwater Creek Watershed area, enclosed within dashed border of Fig. 4. (From Kocin, 1979).

Figure 6. Surface heat fluxes over the Clarksville, TN area, 22 August 1978 at about 1330 LST. Values are in Wm^{-2}. (From DiCristogaro, 1980).

Figure 7. The mean ground-level point concentration ($\overline{\chi}$ (x,0)) as a function of the downstream distance from an elevated source for H_o = 200, 50 and 10 Wm^{-2}. (From DiCristofaro, 1980).

Figure 8. Successive enlargement of Washington, D.C. heat island for HCMM nighttime infrared image, 11 June 1978, approximately 0230 LST (white represents warmer temperatures, black colder temperatures). The top picture contains almost the full HCMM image. The lowest panel contains the 128 x 128 pixel working area.

Figures

Figure B-1. Surface temperature analysis (°C) over Washington, D C. obtained from the HCMM satellite on 11 June 1978, approximately 1330 LST.

Figure B-2. Same as Figure B-1 but for the nighttime temperature analysis, approximately 0230 LST, 11 June 1978.

Figure B-3. Same as Figure B-1 but for surface heat fluxes in units of W m^{-2}

Figure B-4. Same as Figure B-1 but for evaporation fluxes.

Figure B-5. Same as Figure B-1 but for moisture availability M.

Figure B-6. Same as Figure B-1 but for thermal inertia P in units of cal $cm^{-2}K^{-1}sec^{-\frac{1}{2}}$ (note that approximately 400 TIU (400 W $m^{-2}K^{-1}sec^{\frac{1}{2}}$) equals 0.01 cal cm^{-2} $k^{-1}sec^{-\frac{1}{2}}$).

Figure C.1. Temperature analysis over Pennsylvania, determined from HCMM measurements for 11 June 1978, approximately 0230 LST. Mt. Nittany is labelled M, State College with an S. The Barrens is located with a dot and labelled B.

Figure C-2. Enlargement of the surface temperature analysis (in ^{O}C) over the Barrens region (enclosed by a border in Figure C.1).

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List of Publications and Public Presentations Involving HCMM

1. Publications in Refereed Journals

Carlson, T. N., 1981: Central Pennsylvania's Barrens: A view from space. Bull. Amer. Meteor. Soc., 62, (in press).

Carlson, T. N. and DiCristofaro, D. C., 1981: The effects of surface heat flux on plume spread and concentration: An assessment based on satellite measurements. (Submitted to Remote Sensing of Environment).

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2. M.S. Theses

DiCristofaro, D. C., 1980: Remote Estimation of the Surface Characteristics and Energy Balance Over an Urban-Rural Area and the Effects of Surface Heat Flux on the Plume Spread and Concentration. M.S. Thesis, Department of Meteorology, The Pennsylvania State University.

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Kocin, P. J., 1979: Remote Estimation of Surface Moisture Over a Watershed. M. S. Thesis, Department of Meteorology, The Pennsylvania State University.

3. Public Presentations on Subject of Thermal Imagry Using HCMM or NASA Aircraft Supplemental Data. Made at

Penn State Meteorology Seminar Series, December 1978.

Office of Remote Sensing of Earth Resources (ORSER) Seminar Series, December 1978.

University of Maryland Seminar Meteorology Seminar Series, February 1980.

International meeting on preliminary HCMM results in Ispra, Italy, March 1980.

Publications (Continued).

Meeting on preliminary final results at NASA, Goddard Space Flight Center, June 1980.

Meeting on final results of HCMM at NASA, Goddard Space Flight Center, November 1980.